Impacts of windbreak shelter on crop and livestock production

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Abstract

Agroforestry (the integration of trees into agricultural landscapes) has been promoted, in Australia and elsewhere, as a way to increase farm productivity by providing a wide range of benefits. Despite this, adoption of agroforestry in Australian agricultural systems remains low. To implement agroforestry, farmers must be convinced the benefits of including trees outweigh the costs. This review evaluates the available quantitative data on shelter benefits with emphasis on Australian conditions, identifies key research gaps and determines if there is sufficient knowledge to make accurate predictions about impacts on farm productivity.

Availability of quantitative data on windbreak shelter benefits was examined in five key areas; water use and evaporation, crop/pasture production, livestock mortality, livestock productivity and the capacity to model impacts of windbreaks on crop/livestock systems. Good quantitative data exists for many areas, particularly for changes in environmental conditions following tree establishment, however there were many gaps in key areas. Importantly, the ability to predict crop growth under spatially and temporally variable environmental conditions and the impact of windbreaks on livestock productivity is not yet able to be meaningfully quantified. Thus modelling the profitability of windbreaks is difficult and existing models require additional quantitative data to validate and improve them.

Introduction

The strategic addition of trees to farms produces a range of benefits, including: reducing land degradation, diversifying income streams, increasing biodiversity, carbon sequestration and increasing the national timber resource (Race and Curtis 1997; George *et al.* 2012). Due to these benefits, globally many governments have encouraged the establishment of trees on farms, for example Australia's Carbon Farming Initiative (2012) and the Emission Reduction Fund (2014). Yet in Australia, adoption by farmers remains low (Stewart 2009) particularly in comparison to Europe, South-East Asia, Sub-Saharan Africa and the Americas (Zomer *et al.* 2009). Many causes of low adoption have been suggested, particularly economic considerations such as the increased time and finances required to establish trees, and the uncertainty around future markets for timber (Race and Curtis 2007). However, the benefits of trees extend beyond wood production to include potential gains in crop and animal yields due to the provision of shelter. Both timber and non-timber benefits must be quantified to allow mangers to fully assess the economic impact of establishing trees on broader farm finances.

Short to medium-term benefits of tree establishment in agricultural landscapes, such as increased agricultural yield due to shelter, may make trees more attractive to land managers than future timber yields, particularly when tree rotation lengths are sometimes longer than land managers tenure (Race and Curtis 2007). Focusing on these shorter-term benefits has been successful in France where legislating and encouraging agroforestry as an agricultural input rather than a forestry enterprise has resulted in high levels of adoption (Place *et al.* 2012). However, adoption of new agricultural practices relies on land managers understanding the relative advantage of the practice and this is often achieved through trial evaluation (Pannell *et al.* 2006). It is likely that propspective adopters will be more convinced if demonstrated agroforestry benefits are based in similar environments, hence, there is a need for quantitative evidence demonstrating the impacts of shelter derived agroforestry benefits in Australian systems.

In Australian systems, it has been suggested that up to 10 percent of a farm, in high rainfall grazing areas, could be used to grow trees without any agricultural yield loss (Bird 1990; Stewart and Reid 2006). However, these figures are based on assumed benefits to plant growth and livestock survival that, to date, have not been tested and validated with sufficient quantitative data. Aside from the five year Australian National Windbreak Program (1993-1997), information on agroforestry systems in Australian systems tends to rely on 'grey' literature e.g. government reports, often based on assumed benefits or word of mouth. Therefore, it is important to determine if in-depth studies/analysis are needed to confirm the perceived benefits of on farm tree plantings and in what areas information is lacking.

This review explores and synthesises published information on the shelter benefits (i.e non-wood products) that agroforestry systems can have in Australia. In particular, this review aims to;

1. Identify the key research areas required to quantify the shelter derived agricultural benefits of agroforestry systems',
2. Review the quantitative data in each identified area, and
3. Identify research gaps that are limiting our ability to predict the economic or production outcomes of establishing agroforestry.

We have limited our discussion to windbreaks/shelterbelts (hereafter referred to as windbreaks) as there are many different types of agroforestry systems (e.g. silvopastoral, alley cropping, windbreaks), which have varied responses and impacts on farm productivity. Windbreaks are a common form of agroforestry in Australia and are designed to minimise damaging winds in stock and crop/pasture systems. Windbreaks refer to a single, or multiple rows of established trees that are situated on the paddock periphery, or internally at strategically located distances, usually perpendicular to the direction of the most damaging winds. Windbreaks are often planted for their short to medium-term benefits, and therefore differ from farm woodlots, which are typically planted as a long-term fibre crop, with a return not expected until harvest. Due to their size and porosity, woodblocks will likely differ in their impact on adjacent paddocks compared to windbreaks.

Key research areas for windbreak derived agricultural benefits

Windbreaks produce a range of benefits and costs to agricultural systems. The effect of windbreaks on airflow over sheltered pastures/paddocks is well studied, both internationally (Peri and Bloomberg 2002; Brandle *et al.* 2004) and, in Australian systems, particularly through the Australian National Windbreak Program (Cleugh 1998, 2002a). Reducing wind-speeds creates a sheltered zone, typically occurring 3-20 tree heights away from the windbreak (Cleugh *et al.* 2002) and in turn affects many agriculturally important environmental parameters including microclimate (temperature, relative humidity), soil erosion, and hydrology (Kort 1988). Windbreak induced environmental changes have flow on effects to crop yield and/or water use/evapotranspiration (Nuberg and Mylius 2002). While shelter effects on yield can be positive, windbreaks also create a competition zone where trees cause a reduction in plant productivity via competition for water, nutrients and light: this zone usually occurs within one to two tree heights of the windbreak (Nuberg 1998).

Livestock productivity and mortality can be impacted via windbreak induced changes in pasture productivity and environmental conditions (e.g. temperature and wind-speed) (Collier *et al.* 2006; Pollard 2006). Windbreaks may also have negative interactions with livestock for example, adverse interactions via poisoning or harbouring pests, although the majority of negative interactions can be minimised through tree choice and windbreak design (Gregory 1995).

Land managers often find agroforestry systems challenging to adopt because of their perceived complexity. However, this perceived complexity can be overcome through the provision of empirical results from trials (Stanley *et al.* 2006). Biophysical and bio-economic modelling supported by robust empirical data has the potential to assist farmers in decision making around establishment of agroforestry systems. Decision support tools need to be capable of evaluating the impacts of trees on the key aspects of agricultural systems, including tree, crop and animal yields, and therefore income under various scenarios. Ideally, such models will be able to accommodate various windbreak types and configurations, type of agricultural enterprise, and how they interact with micro- and macro-climatic factors.

We identified five areas that should be considered when quantifying the benefits of potential windbreaks in agricultural landscapes:

1) Impact of windbreaks on water use and evapotranspiration,
2) Impact of windbreaks on crop and pasture production
3) Impact of windbreaks on livestock mortality
4) Impact of windbreaks on overall livestock productivity, and
5) The capacity to model economic benefits of windbreaks.

Below we review available Australian data in the above areas and identify key research gaps; however it is important to recognise that trees provide other benefits to agricultural enterprises not accounted for in the above categories, including; reduced erosion, improved nutrient and water management, promoting pollinators, carbon storage and improved aesthetics and farm value.

Shelter impacts on paddock-level water use and evapotranspiration.

Windbreaks alter paddock-level water use via three main mechanisms: 1) trees competing with agricultural crops for water in the competition zone, 2) reduced evapotranspiration in the sheltered zone, and, 3) reduced micro-droplet evaporation loss/drift in irrigated systems.

The first mechanism is well described. Trees compete for water with adjacent agricultural crops, intercept rainfall (Radcliffe 1985) and create rain shadows within paddocks (Woodall and Ward 2002) creating depressed yields in the competition zone (Bird 1998). In Australian systems, tree water use, water source (White *et al.* 2002) and how hydrological impacts vary with differing ground water depths (Brooksbank *et al.* 2011) are well studied. While the competition effects are important to consider, this review focuses on the second two mechanisms as they are shelter derived impacts.

Reduced evapotranspiration beyond the competition zone is commonly observed in Australia and internationally. Windbreaks reduce evapotranspiration in the sheltered zone through a combination of altered air movement, direct interception of solar radiation and by altering plant transpiration through changes in growth rate and physiology (Table 1). Lower wind-speeds on the leeward side of windbreaks reduce evapotranspiration (Messing *et al.* 1998; Nuberg and Bennell 2009; Koh *et al.* 2010) which increases water availability to plants (Campi *et al.* 2012), extending the growing season in dryland systems, or reducing irrigation requirements.

Table 1 approximate position

Windbreaks conserve water in agricultural systems predominantly by lowering air temperatures and wind-speeds (Table 1). This result is well demonstrated across Australian and New Zealand studies and especially through the Australian National Windbreak Program (studies published between 1998-2002, Table 1). International studies provide consistent results demonstrating benefits on soil water retention in the sheltered zone, but a net water loss closer to windbreaks due to tree consumption (Stirzaker *et al.* 2002).

Windbreaks can increase overall paddock productivity by reducing evaporation increasing the efficiency of production per unit of water (Ali and Talukder 2008). While shelter impacts on evapotranspiration are well studied, only one Australian study (Table 1), Nuberg and Mylius (2002), measured the associated changes in crop yield and they found that wheat grown in the shelter of a windbreak used more water which resulted in greater plant biomass, but not a higher grain yield. Linking windbreak-induced water use change and crop yield is also rare in the international literature with only a single study identified (Rosenberg 1966). This study found increased depletion of soil water in sheltered plots and equated that to greater plant use and in some cases, but not all, this correlated to an increase in yield. Furthermore, as noted by Cleugh (1998) plants germinated in a sheltered environment may have different physiology (e.g. leaf size and stomatal resistance) so while the environmental evaporative demand might be lower, the plant water use may be similar to that of unsheltered plants. Additionally, Cleugh and Hughes (2002) concluded that windbreak induced changes in water fluxes are not directly correlated with changes in other environmental characteristics such as wind. It is apparent that the understanding of how climatic changes induced by windbreaks impacts on plant yields is lacking, therefore, additional data is needed to relate environmental changes, including evapotranspiration, to the impact they have on returns to the land owner.

The third mechanism by which windbreaks alter water use, is through altering paddock-level water use in irrigated systems. This area has received less attention than the first two mechanisms. By reducing wind-speeds, windbreaks can prevent irrigation drift and reduce irrigation requirements (De Vries *et al.* 2010; Kilaka 2015). The quantity of water supplied through irrigation at a paddock level could be reduced, via lowered evapotranspiration and spray drift, by 10-60% when shelter was effectively used (Table 1). The ability of windbreaks to reduce spray drift potentially lowers water costs, makes more water available elsewhere, or lowers costs of agrichemicals. This area of research has, to our knowledge, only been examined once in Australasian systems by Kilaka (2015) who showed that when windbreaks were removed extra irrigation was required. This appears to be an important area of research as irrigation, especially as centre pivot irrigation increases on Australian farms and future climate conditions may put further stress on water resources. In addition to minimising drift of irrigation water, further benefits are likely by minimising the drift of chemical sprays on farms (Ucar and Hall 2001; Felsot *et al.* 2011), reducing wastage, pollution of waterways, and damage to non-target crops.

As well as potential for direct benefits and costs to agricultural productivity, windbreaks can provide other benefits for water management. Through reducing soil erosion, slowing water movement and creating root channels, trees can increase the ability of water to infiltrate and store in soil (Young 1989). Trees can reduce rising salinity by utilising water during fallow periods, accessing deep soil water (Oliver *et al.* 2005), intercept fresh water before it contributes to rising saline water table (Abel *et al.* 1997; Bennett and Cattle 2014), and limit the runoff of agricultural chemicals into water courses (Ucar and Hall 2001). These benefits may be harder to quantify economically, but will serve to protect against future economic losses by improving the environmental and soil health.

Impact on pasture/crop yield

Crop yields generally decrease in the competition zone, but increase in the sheltered zone. Increased yields are attributed to multiple factors; reduced wind damage, decreased evapotranspiration and more favourable microclimate conditions e.g. temperature and relative humidity (Bird *et al.* 1992; Cleugh 1998; Cleugh *et al.* 1998). In the majority of studies, yield increases in the sheltered zone overcome the yield loss in the competition zone however, some studies have reported no responses at the paddock scale and others have reported net yield loss (Table 2).

Table 2 Approximate position

Australian studies show high variability in the effects of windbreaks on agricultural productivity. These studies were predominantly carried out in the 1990's (Bicknell 1991; Burke 1991) and by the Australian National Windbreak Program (see programme review by Cleugh *et al.* (2002)) (Table 2). In temperate Australian systems crop yields have been reported to increase by between 0 – 47 % (Nuberg 1998) (Table 2), however some studies show no yield increase (Bird 2003) and others report net yield reductions (Oliver *et al.* 2005). Variability in yield responses has been attributed to three main areas; environmental differences between sites, differential responses between crop species, and temporal environmental changes (both between seasons and across years). Understanding variability in crop species responses to windbreaks is currently a key limitation in being able to accurately predict windbreak derived agricultural benefits. The factors influencing crop species variability are discussed below.

Variation in crop response to windbreaks between sites and years is in part related to changes in environmental conditions. In Australia, windbreak shelter benefits occur more in areas where rainfall limits crop and/or pasture growth (Cleugh *et al.* 2002). This is also the case internationally, for example, in Northeast China windbreak benefits on plant yield occurred most at dry sites (Zheng *et al.* 2016). Additionally, windbreaks tend to increase crop growth in areas exposed to high wind in Australia (Cleugh *et al.* 2002; Bennell and Verbyla 2008), and internationally e.g. Patagonia (Peri and Bloomberg 2002). The more consistent benefits of windbreaks in dry, hot or windy conditions may mean that windbreaks could be employed as insurance against years when these conditions occur. Importantly, windbreaks may be more advantageous for adapting farms and farm businesses to future climates, with hotter, drier, and more extreme events predicted to occur. In addition, the impact of windbreaks on yields due to hydrological changes is likely to depend on the yearly rainfall distribution patterns (Nuberg and Mylius 2002). However, these studies only propose the conditions under which windbreaks will be most effective and to our knowledge, no study has specifically addressed changes in windbreak effectiveness with variation in environmental conditions.

Studies reported in Table 2 were conducted on a mixture of crop and pasture species. Variation in growing/producing times between species may interact with seasonal environmental variation and drive some of observed variability in windbreak effects between studies and species. The scale of microclimatic changes induced by trees varies seasonally (Baker *et al.* 2016), which may explain variability between crop growth and yield responses reported (Table 2). Seasonal differences in the scale of windbreak effects is an important factor to consider, for example, in areas where hot and dry conditions are more likely at the end of the growing season, windbreaks could potentially extend the growing season. Variability between crop species responses to windbreak effects is also likely driven by different susceptibility to climate or other windbreak benefits e.g. increased pollinator load (Wratten *et al.* 2012).

Impact of shelter on livestock mortality

In temperate Australian conditions windbreaks can prevent livestock mortality from extreme cold (Hinch and Brien 2014) and heat stress (Gregory 1995). Shelter reduces the risk of extreme environmental conditions, particularly wind-chill, and heat-stress induced by direct radiation. The importance of providing shelter from extreme environmental conditions has been recognised by many livestock certification schemes e.g. Australian certified organic standard, 5-step animal welfare standard, which may be an additional benefit of agroforestry systems.

A recent review of Australian studies on lamb mortality by Hinch and Brien (2014) suggested that research on the impact of windbreaks on lamb mortality had not advanced since work by Lynch and Alexander e.g. (Lynch and Alexander 1976; Alexander *et al.* 1980) (Table 3). Much of the information on lamb mortality is derived from New Zealand studies (Table 3) due to research following severe storms in 1992 (Gregory 1995).

Table 3 Approximate position

It is clear from the majority of Australasian studies (Table 3) that windbreaks reduce mortality of newborns lambs born in cold, wet and windy conditions. Studies observing little or no reduction in lamb mortality (Pollard and Littlejohn 1999; Robertson *et al.* 2011) are most likely due to a lack of adverse conditions over the study period. Broster *et al.* (2012) modelled the impact of severe weather conditions on the chill index and found that the impact of shelter varied with location and season depending on prevalence and timing of wind and wind chill.

There is a need to differentiate and quantify the benefits of different shelter types, for example, reports in Table 3 do not differentiate between the benefits of tree windbreaks and man-made shelter. While studying general shelter responses may serve to encourage further establishment of shelter in paddocks, it cannot be used to model the overall costs and benefits of tree windbreaks as there are likely differences in the effects between shelter types. Even within windbreaks, shelter values will change with configuration, topography, species, age, density, and management, which are variables that should be recorded in such studies.

More research is required to understand how windbreaks affect livestock mortality. Most studies in this area are based on research into livestock thermodynamics at different temperatures/wind-speeds and the assumptions that windbreaks alter these conditions, and livestock utilise altered areas. In particular there is a lack of research on the impact of reduced wind-chill on calf mortality, and the potential benefits of reduced heat stress due to windbreaks on both calf and lamb mortality. Current evidence on livestock mortality is often anecdotal (Gregory 1995), survey based e.g. Pollard (1999) or based in specific systems e.g. man-made fences (Lynch and Alexander 1977) or grass windbreaks (Lynch *et al.* 1980b). There remains a lack of experimentally obtained quantitative data since studies done in the 1970's on man-made fences (Table 3) and therefore, research in tree windbreak systems is required.

Shelter impacts on livestock productivity

Windbreak shelter can potentially improve livestock productivity, e.g. liveweight gain, milk or wool production. Several studies have explored the impact of adverse environmental conditions on productivity (see Bird (2003) for a review on dairy cow production), based on knowledge of the thermal dynamics and energy use of livestock (McArthur 1991). However, there is limited quantitative data on productivity changes in tree windbreak systems. Man-made windbreaks are reported to increase production for both sheep and cattle (McIlvain and Shoop 1971; Holmes *et al.* 1978; Lynch and Donnelly 1980), but artificial windbreaks do not simulate the negative impacts of tree competition on pasture productivity, and will have different environmental impacts to trees due to differing porosity and size. Changes in microclimatic conditions e.g. higher temperature and reduced wind-chill, which are known to occur in association with windbreaks (Cleugh 1998), are likely to be beneficial to livestock productivity. Alternatively, tree shading can decrease livestock productivity (Mader *et al.* 1997; Ainsworth *et al.* 2012) due to less time spent foraging and reduced forage growth.

However, there are few quantitative studies on livestock yields associated with windbreaks. Internationally, studies generally focus on windbreak impacts during winter and have shown small to no benefits (Olson *et al.* 2000; Olson and Wallander 2002). Heat stress is an important issue for livestock production and as shade and wind-flow are important determining factors of heat stress (Tucker *et al.* 2015), windbreaks may play an important role. However, to our knowledge no studies have assessed the impact that windbreak induced changes in environmental conditions have on the heat stress or productivity of livestock.

While there is a good understanding of the thermal dynamics that impact livestock productivity, our current understanding is hindered by a limited ability to account for behavioural responses to the environmental conditions (Caton and Olson 2016). Therefore, it is important to test livestock responses in actual windbreak systems as it will account for both environmental and behavioural changes. Although studies in NSW in the 1970's and 80's monitored behaviour and productivity changes in sheltered paddocks (Table 4), shelter was created using either man-made fences or small grass windbreaks. Further research should extend this work into treed systems, which will alter environmental conditions to differing degrees and scales.

Table 4 Approximate Position

As yet there is insufficient evidence to draw any conclusions about the impact of windbreaks, especially tree windbreaks, on livestock productivity under Australian conditions (Table 4). While numerous reports have found that heat and cold stress can result in reduced yields (Bird 2003), there is currently a limited evidence base to demonstrate that the modified microclimates associated with windbreaks are sufficient to impact livestock productivity. However, it has been demonstrated that sheep utilise shelter under inclement weather conditions (Taylor *et al.* 2011) and therefore, it is reasonable to assume that this confers a productivity benefit based on the energy balance studies reported above.

Modelling the impacts of windbreaks

The ability to model agroforestry impacts on both biophysical responses and yield is crucial for accounting for revenues and costs from both the agricultural, environmental and forestry aspects of windbreaks (Sudmeyer and Flugge 2005; Donaghy *et al.* 2010). Modelling capabilities that allow users to explore the impacts of differing management techniques, tree and crop species, products, and spatial/temporal configurations on the profitability of agroforestry systems are needed. The variability of agroforestry outcomes, especially in species responses and changes with environmental conditions, requires bioeconomic models to account for this variation, and provide a potential range of economic predictions to the end user; however for many aspects, such as the areas addressed in this review, more data is required. Models based on robust quantitative data will be more powerful and could help guide management strategies to ensure that agroforestry is a profitable part of the farm enterprise (e.g. see Sudmeyer *et al.* (2012) in mallee systems). With sufficient quantitative data, modelling could allow the extrapolation of agroforestry outcomes to examine the impact of temporal changes which are otherwise unachievable due to time and logistical constraints.

Many models predict yield and economic returns of agroforestry systems, though these models have generally been developed for specific locations and agroforestry types (Luedeling *et al.* 2016). Many agricultural production models tend to focus on systems other than windbreaks e.g. alley-cropping or silvo-pastural, therefore, caution is recommended when applying them to other systems and beyond their derived locations.

Several models have been developed to predict individual components of windbreaks e.g. tree-crop competition (Mayus *et al.* 1998), evapotranspiration/water use (Campi *et al.* 2012) and overall crop yield (Easterling *et al.* 1997). This modelling has occurred in Australian systems (Table 5) however, there are few models that include multiple important economic components e.g. crop, livestock, water and agrochemical. As Carberry *et al.* (2002) demonstrated, focusing on a single benefit of agroforestry systems can misrepresent their economic potential. The economic feasibility of windbreak systems needs to accommodate for a combination of effects and models need to encompass this.

Table 5 Approximate Position

While some studies estimate the combined economic impact of multiple agroforestry components e.g. Loane (1991) and Huth *et al.* (2003), the ability to confidently model multiple agroforestry components is limited by the availability of quantitative data. For example, estimating the impact of shelter on livestock production is very challenging as all the components of the system have yet to be quantified. While studies such as Young *et al.* (2014) focused on the economic benefit of windbreaks on reduced lamb mortality, if the potential increases in fodder, reduction in water use and the improved productivity of the livestock as well as the multiple other benefits of windbreaks were included, then it may improve the economic accuracy of predictions and the appeal of agroforestry systems.

Outside of agricultural benefits, other benefits also need to be considered e.g. use of trees for fodder (Patabendige and Lefroy 1992; De Koning and Milthorpe 2008; McHenry 2013), use of trees for wood production and carbon (Chavasse 1982), ability to mitigate rising salinity (George *et al.* 2012), biodiversity (Jose 2009), ecosystem services e.g. pest control, pollination (Zhang *et al.* 2007; Wratten *et al.* 2012) and land value benefits (Polyakov *et al.* 2014). While for some of these additional components, the ability to model outcomes already exists e.g. wood production from plantations, additional benefits still need to be incorporated into agroforestry based models.

Temporal impacts of the windbreak tree rotation provide additional complexity that must be considered. For example, a suitable agroforestry model needs to consider how the benefits change over time from establishment to mature trees to tree removal/death (Luedeling *et al.* 2016), particularly if windbreaks are implemented for wood production. Agroforestry models have been developed that do incorporate the lifespan of the tree component (Jones and Sudmeyer 2002; Meinke *et al.* 2002), although these models rely on data where variation in response is due to tree height and do not account for changes in shelter characteristics between young and old windbreaks and changes due to silvicultural management. This leaves a clear gap in our capacity to predict and model potential economic benefits temporally in agroforestry systems.

Conclusions and recommendations

In Australian agricultural systems, agroforestry has the potential to increase yields and provide net positive economic benefits to farmers. The impact of agroforestry systems on agricultural productivity has been synthesised from numerous case studies, reviews and grey literature. However, while the effects of windbreaks are numerous, they are highly variable and there is a lack quantitative data to drive decision making in many key areas. In each of the research areas examined, we identified significant data gaps (Table 6) that need to be filled to accurately predict the agricultural impact of windbreak establishment.

Table 6 Approximate Position

Key gaps in our knowledge (Table 6) inhibit our ability to reliably estimate the impact of establishing windbreaks on agricultural productivity. In particular, yearly and seasonal variation in the responses of crop yields to windbreaks limits the ability to accurately model windbreak impacts. It is likely that windbreaks provide greater benefits in years with climatic extremes, and as a result may serve as a form of crop/livestock insurance from extreme conditions. Protection from extreme environmental events is likely to increase in importance due to the projected increase in climate extremes (Easterling *et al.* 2000). Understanding the relative importance of environmental drivers on the impact of windbreaks (Table 6) will increase the capacity to model windbreak benefits under changing climates. The capacity to model crop yield responses is also limited by the lack of studies examining the complex relationship between windbreak induced changes in evapotranspiration and the subsequent impact that has on plant physiology and therefore crop and pasture yields. The impact of agroforestry systems on paddock-scale water dynamics requires more data and is an area that has strong potential to improve agroforestry profitability particularly for pivot irrigation systems which are susceptible to water loss through spray-drift. Windbreaks in irrigated systems potentially reduce water use and prolong soil water availability in dryland systems.

Windbreak impacts on livestock productivity is another area that requires further study to allow better prediction of livestock productivity with shelter. The impact on shelter is complex and includes changes in mortality, animal thermodynamics and windbreak induced changes in pasture production. The cumulative effects of windbreaks on livestock productivity are well understood and therefore the capacity to provide accurate economic estimates of the impact of windbreaks is limited. Increasing predictability will enhance farm-scale decision making of when and where windbreaks will be beneficial. For example, in Australia variation in paddock size between states may determine the capacity for windbreaks to be economically viable e.g. average paddock size is 449 ha across Queensland/Western Australia compared to 77 ha across Tasmania/Victoria/New South Wales/South Australia (ABS 2017). Even in larger paddocks, the net positive effect of windbreaks may still justify their establishment, and/or establishment of within-paddock shelter, if it is shown to make a net positive contribution to whole farm profitability.

Tools such as bioeconomic or biophysical models are needed to guide farm based decisions on agroforestry. Confidence in these tools requires them to encompass multiple agroforestry drivers and to be based on robust data as benefits of individual aspects of agroforestry can be small and often do not offset establishment, maintenance and competition costs. However, the literature identified in this study, shows numerous gaps in quantitative data which limits this ability and as a result the benefits of agroforestry often rely on assumptions and/or anecdotal experience. For example Bird (1990) suggested that 10 percent of farms could be planted without negatively affecting yield, based on assumptions without data. Quantitative data is needed, both to inform the model assumptions, and to validate model outcomes. If this and other benefits are confirmed with data, the business case for adoption of agroforestry systems would be clearer, particularly for land-managers who rely on the agricultural benefits derived from agroforestry.

Conflicts of interest

The Authors declare no conflicts of interest.

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Table 1: Published impacts of agroforestry systems on paddock evapotranspiration in Australia and New Zealand. Shelter type refers to mechanism by which shelter was generated in the study. TH refers to tree heights * Includes Australian studies

Publication	Windbreak type	Location	Results	Conclusion
Bird (1998)	Various	Global*	NA (review)	Soil evaporation reduced and soils with shelter store water for longer.
Cleugh (1998)	Tree	Theoretical	Environmental changes due to windbreaks alter evapotranspiration.	Effect of windbreaks is complex, and effects vary depending on plant water status and weather conditions.
Cleugh (2002a)	Tree	South-East Australia	Evaporative demand reduced up to 6 TH.	Windbreaks reduce evaporative demand, but effects depend on numerous factors including time of day.
Cleugh & Hughes (2002)	Artificial	NA	Heat flux (evaporative flux) reduced in quiet zone (0-5 TH) and enhanced at 8-12 TH.	Evaporation fluxes and microclimate patterns differ to near-surface wind-speeds, therefore the drivers of plant yields may be variable over distance.
Hall *et al.* (2002)	Tree	Western Australia	Soil water reduced within 3 TH.	Windbreaks reduce stored water and results in halving of water available to plants.
Nuberg & Mylius (2002)	Artificial	Adelaide	Shelter reduced early season evaporation.	Sheltered sites retained soil water for longer periods, this increased wheat biomass but not yield.
Sudmeyer *et al.* (2002b)	Tree	Western Australia	Soil water was reduced within 1.7 TH.	Reduced soil water near windbreak a result of uptake by trees.
De Vries *et al.* (2010)	Tree	New Zealand	Shelter reduced evapotranspiration by up to 50%.	By modelling irrigation use showed that shelter can reduce farm water requirements by 16%.
Kilaka (2015)	Tree	New Zealand	Required irrigation increased 38-64% without windbreaks.	Windbreaks conserve water due to reduced spray losses and decrease in evapotranspiration.

Table 2: Published impacts of windbreaks on pasture and crop growth for Australian conditions. Global reviews include studies based in Australian conditions.

Publication	Windbreak type	Location	Result	Conclusion
Sturrock (1981)	Various	New Zealand	+35%	Shelterbelt standards are currently held back by lack of information.
Kort (1988)	Tree	Global*[1]	- 8 – + 203%	94 out of 97 shelterbelts increased crop yield but varied with species & environment.
Bicknell (1991)*[2]	Tree	Australia (W.A)	0-30% increase	Increase was species dependent. Lupins 27-20%, oats 0-10%.
Burke (1991)*[2]	Tree	Australia (Vic)	+0-45% (sheltered zone), -31-49% (competition zone)	Increased observed varied with species and direction of windbreak.
Hawke and Tombleson (1993)	Trees	New Zealand	Overall decrease	Paddock level decrease but 15% increase at peak shelter.
Sun and Dickinson (1994)	Tree	Australia	+6.7% yield, +11% quality	Reduction in competition zone but increase in sheltered zone resulted in overall paddock increase.
Bird (1998)	Tree	Global	+ 12 – 60%*[3]	Impact hard to detect as effect size is small and variability between and within paddocks overwhelms response.
Nuberg (1998)	Various	Global	+ 0 – 47%	26 out of 31 studies showed yield increases 3 decreased but only measured competition zone. Results highly temporally and spatially variable.
Bird *et al.* (2002a)	Tree	Australia (Vic)	-28% (competition zone)	Significant reduction in competition zone (0-1TH) but no difference in sheltered zone.
Bird *et al.* (2002b)	Artificial	Australia (Vic)	+8-10% annually	Small but consistent increase in pasture in sheltered plots. Trend reversed in wet conditions.
Nuberg *et al.* (2002)	Tree	Australia (SA)	+0-81%	Largest increase in the dry season.
Sudmeyer *et al.* (2002a)	Tree	Australia (WA)	0-25%	Increase only observed in sites with high winds.
(Sudmeyer and Scott 2002)	Tree	Australia (WA)	-2.8%	Consistent decrease in competition zone and only small increase in sheltered zone, although increased in dry year.
Cleugh *et al.* (2002)	Various	Australia	No response or small increase.	Overall yield results are small but benefits were enhanced in dry years and when wind was a limiting factor.
Oliver *et al.* (2005)	Tree	Australia	- 24 – + 17%.	Across all paddocks 4 out of 21 had a net positive yield increase, but varied with year.

Sudmeyer & Speijers (2007)	Artificial	Australia	Yield decrease within 1.5–3 shelter heights	Shading has a negative impact on crop yield. Variable between species.
Bennell & Verbyla (2008)	Tree	Australia	+ 0 – 19 %	Showed strong spatial, temporal and species variation with. Effects stronger in dry and windy years.

*[1] Reported results from temperate systems only *[2] results derived from (Nuberg 1998) *[3]results exclude studies previously reported by Kort (1988).

Table 3: Published reviews of the benefits of shelter on livestock mortality.

Publication	Windbreak type	study	Location	Conclusions
Miller (1968)	Artificial	Sheep	New Zealand	No response in live-weight, although lambs utilised shelter.
Egan *et al.* (1972)	Artificial	Sheep	Australia (Victoria)	13% increase in early survival. Benefit driven by wind.
Lynch and Alexander (1977)	Grass & artificial	Sheep	Australia (NSW)	50% reduction in mortality. Shelter used more in inclement weather.
Alexander *et al.* (1980)	Grass	Sheep	Australia (NSW)	10-32% survival increase. Driven by wind velocity.
Lynch *et al.* (1980b)	Grass	Sheep	Australia (NSW)	50% reduction in mortality.
Bird *et al.* (1984)	Trees	Sheep	Australia	Shelter reduces lamb mortality by up to 50%.
Gregory (1995)	Trees	Livestock	New Zealand	Shelter reduces mortality but effect is most prevalent in young lambs and shorn sheep in inclement weather.
Pollard (2006)	Various	Sheep	New Zealand, Australia	Wind shelter reduced mortality by 3-13% of single lambs, and 14-37% of twins.
Fisher (2007)	Various	Livestock	New Zealand	Shelter must be provided in situations where the animal would use it.
Hinch & Brien (2014)	Various	Sheep	Australia	Overall shelter reduces mortality rates but more research is required.

Table 4: Published studies and reviews on the effect of windbreaks on livestock productivity.

Publication	Windbreak type	Animal	Location	Results	Conclusions
Gregory (1995)	Tree	Sheep, Cattle	Australia, New Zealand	NA (Review).	Shelter minimises the weather conditions which reduce productivity. Benefits may be restricted to extreme conditions. Much of the evidence is anecdotal.
Bird (2003)	Various	Dairy Cows	Global	NA (Review).	Extreme environmental conditions reduce productivity. Shelter can limit losses but evidence is not conclusive in southern Australia.
Alexander and Lynch (1976)	Grass	Sheep	NSW	Lambs with shelter 12g heavier at 21 days.	Shelter protects lambs and gives them early growth advantage.
Lynch & Donnelly (1980)	Artificial	Sheep	NSW	Shelter increased wool produced per day.	Increase in productivity is linked to increased pasture growth that was observed.
Lynch *et al.* (1980a)	Artificial	Sheep	NSW	Energy intake was 15-21% higher with shelter	Energy intake is linked to live-weight and wool production.
Pollard & Littlejohn (1999)	Artificial	Sheep	New Zealand	No productivity differences.	Lack of difference between shelter and no-shelter may be due to the lack of extreme conditions.

Table 5: Publications describing the modelling of economic benefits of agroforestry systems.

Publication	Shelter type	Model	Location	Results	Conclusions
Nuberg (1998)	Windbreak	NA (Review)	Global	Lack of data on the net yield impact.	Economic models need to be developed.
Bird (1990)	Windbreak	Economic - whole farm (tree, crop & livestock)	Australia	If 5% of area used as shelterbelts long-term profitability increases.	10% of the farm as close spaced shelterbelts can be used without reduced yield.
Loane (1991)	Various	Economic – crops, tree and additional components.	Victoria	NA (Model developed not tested).	Data uncertainty and complex interactions reduces certainty of model.
Cleugh (2002b)	Windbreak	Crop yield and microclimate.	Australia	Distance to windbreak alters evaporative demand.	Shelter induced changes in evaporative demand only occur intermittently.
Jones & Sudmeyer (2002)	Windbreak	Economic, crop & tree, with temporal component.	Australia	Distance between windbreaks, management and environment alters economic benefits.	Windbreaks profitable when not close together and when damaging wind conditions present.
Meinke *et al.* (2002)	Windbreak	Crop yield, with temporal component.	Australia	Windbreak induced environmental changes can be included in existing crop models.	It is possible to model the effects of windbreaks on a variety of crops in Australian systems.
Huth *et al.* (2003)	Windbreak	Crop & tree yield.	Australia	Cash flow in agroforestry system only exceeds control when trees are utilised.	Modified APSIM model calculates agroforestry yield, allows comparison to broad acre agriculture.
Sudmeyer & Flugge (2005)	Various	Economic impact of root pruning.	Western Australia	Tree management strategies alter the economics of agroforestry	Managing tree competition alters economics of agroforestry systems.
Broster *et al.* (2012)	Windbreak	Environmental model for lamb mortality	Australia	Windbreaks reduce the time which wind-chill is at significant levels.	In high wind-chill areas, windbreaks are an effective measure to reduce mortality.
Sudmeyer *et al.* (2012)	Windbreak	Economic crop & tree	Western Australia	Tree competition is a significant cost	Management can alter profitability e.g. harvest timing, windbreak spacing & root pruning.

Young *et al.* (2014)	Grass hedges	Economic impact of lamb survival.	Australia	Profitability increased if shelter reduced mortality	Shelter in high wind-chill areas shelter increased profit.

Table 6: Research gaps identified that limit the ability to predict the outcomes of windbreak implementation.

Area	**Gap**
Water-use and evaporation	• Quantification of the impact that changes in evapotranspiration has on plant biomass/yield production. • Impact of windbreaks on irrigation spray drift.
Pasture/crop yield	• Understanding the relative importance of environmental conditions which drive crop/pasture responses. • Understanding variation in responses between species. • Understanding variation in response with season/year.
Livestock mortality	• Quantification of the impact that tree windbreaks have on livestock mortality as opposed to other shelter types, particularly for cattle. • Quantification of the impact tree windbreaks have on livestock heat stress.
Livestock productivity	• Field studies detailing the impact of tree windbreaks on livestock productivity.
Windbreak modelling	• Multi benefit modelling that includes tree yield, whole farm water use, crop/pasture/livestock yields and their interactive effects.